Room-Temperature Solid-State Radiation Detectors Based on Spintronics

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***Abstract*– In this paper we are presenting a unique *approach* to solve the thermal background problem encountered in semiconductor nuclear detectors. Our approach addresses above challenge by making a shift from 'electronic detection mechanism' to 'spintronic detection mechanism'. The *proposed methodology* is based on the *hypothesis* that the electromagnetic field associated with the incident nuclear radiation will interact with the spin of the electrons (injected from a ferromagnetic electrode into a semiconductor channel) via the Rashba spin-orbit interaction mechanism. This interaction will result in a precession in the spin polarization of the electrons and as a result the current collected by another ferromagnetic electrode (which will be aligned either parallel or anti-parallel to the first electrode) will change. So, in contrast to traditional semiconductor detectors, where the radiation sensing mechanism depends on the generation and collection of charge carriers, in spintronic detectors, the radiation sensing mechanism will be based on the quantum mechanical precession of the spin of electrons.**

I. INTRODUCTION

A grand challenge in semiconductor nuclear radiation detection technology is to overcome the thermal background problem which hampers the room temperature operation of semiconductor detectors. The ***goal*** of this project is to address the above challenge by using the concept of spintronics. Our ***approach*** is to make a paradigm shift from the presently employed 'electronic detection mechanism' to 'spintronic detection mechanism'. Specifically, in present semiconductor detectors, radiation detection is achieved via the interaction of incoming radiation with the detector material and subsequent generation and separation of charge carriers [1-8]. For achieving high energy resolution, it is essential that the detector material be such that for a given energy deposition by radiation it generates a very large number of charge carriers. This requirement demands the utilization of high-Z and low band-gap semiconductors such as Germanium (Ge) [9-11]. Nuclear detectors utilizing low band-gap semiconductors possess higher resolution compared to other detectors. However, low band-gap detectors suffer from the problem of large thermal background. For reliable operation, these detectors need to be cooled to liquid nitrogen temperature. This increases the over-all operational cost and complexity of semiconductor detectors quite significantly. Moreover, the need of liquid cryogen renders semiconductor nuclear detectors useless for operation in remote areas.

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It is widely believed that the incremental advances to the current semiconductor nuclear detector technology will not be sufficient for developing next generation ultra-sensitive, cost-effective detectors. Such development will require the utilization of entirely new and transformative approaches. Here we are proposing one such innovative approach utilizing the concept of spintronics [12].The proposed approach is based on the hypothesis that the electromagnetic field associated with the incident nuclear radiation will interact with the spin of the electrons (injected from a ferromagnetic electrode into the semiconductor) via the Rashba spin-orbit interaction mechanism [12]. This interaction will result in a precession in the spin of the electrons and as a result the current collected by another ferromagnetic electrode (which will be aligned either parallel or antiparallel to the first electrode) will change. So in contrast to semiconductor detectors, where the radiation sensing mechanism depends on the generation and collection of charge carriers, in spintronic detectors, the radiation sensing mechanism will be based on the quantum mechanical de-coherence of the spins of electrons. Since the absorption of the incident radiation in the semiconductor (and subsequent generation of additional carriers) is not a requirement, wide band-gap semiconductors can be used as sensing media. This will significantly reduce the thermal background problem encountered in conventional semiconductor detectors.

II. SPINTRONIC APPROACH

Spintronics represents a new paradigm of electronics that utilizes both the electron's charge as well as its spin degrees of freedom [13-34] It has the potential to facilitate a new class of radiation detectors with enhanced functionality and performance compared to presently available semiconductor detectors. A fundamental difference between the traditional semiconductor detectors and the proposed spintronic detectors is that the performance of traditional semiconductor detectors depends on how efficiently the charge carriers are generated by the incident radiation and then how efficiently those are separated and collected; on the other hand, the performance of a spintronic detector will depend only on how efficiently the spin of the electrons (already present in the semiconductor channel) is randomized by the incoming radiation.

In the case of a spintronic detector, the physical generation of e-h pairs by radiation is not required. If the incident radiation can perturb the spin of the spin-polarized electrons in the semiconductor channel, it will result in a change in the conductance of the channel and hence a detectable signal. Since in these devices, physical absorption of the radiation and subsequent generation of charge carriers is not required, a wideband semiconductor can be employed as active sensing medium which will significantly minimize the thermal background problem encountered in conventional semiconductor detectors

A. Injection of Spin-Polarized Carriers in Semiconductors:

The most important step in the functioning of a spintronic device is the injection and detection of spin-polarized carriers in the semiconductor channel [13-25]. Optical techniques were used for the above purpose in most of the work performed till very recently [26]. However, optical methods of injecting spins are not very convenient for fabricating actual devices. Moreover, though optical methods work quite well for direct band-gap semiconductors, the same do not work for silicon and germanium based devices due to the indirect nature of their band-gap. Since silicon is widely regarded as the current work-horse of the electronics industry, researchers are very keen on developing non-optical methods of spin injection and detection for silicon based spintronic devices. Despite considerable efforts, efficient injection and detection of spins into semiconductors by non-optical means continued to be a major hurdle in this field. Ferromagnetic metals such as Fe and Ni were used in earlier studies for injecting spin-polarized carriers into a semiconducting transport medium [14,15]. However, in most of the studies the degree of spin polarization of injected carriers was very small (less than 1%) [23]. In order to overcome this, three different approaches have been proposed for the efficient injection of spin-polarized carriers into semiconductors: (a) tunneling spin-polarized carriers from ferromagnetic metals into the semiconductor through an insulator [35], (b) tunneling non-polarized carriers through ferromagnetic insulator, which acts as a Spin Filter [25], (c) using dilute magnetic semiconductors (DMS) which are ferromagnetic and whose conductivity can be tuned to match the nonmagnetic semiconducting transport medium [15,26].

B. NiFe/MgO tunnel-barrier for Spin

Recently in an important study, we achieved the all electrical spin injection and detection of spin polarized carriers using NiFe/MgO tunnel-barrier-contacts[36]. NiFe/MgO tunnel-barrier-contacts arranged in lateral three-probe-geometry were fabricated to create and investigate the flow of polarized electrons in silicon (see fig. 1). The devices were electrically characterized by passing a constant current of 100 μA across the outer two contacts (terminal 1 and 3), while the voltage drop (V) was measured across one outer and one inner contact (terminal 1 and 2) as illustrated in fig. 1.

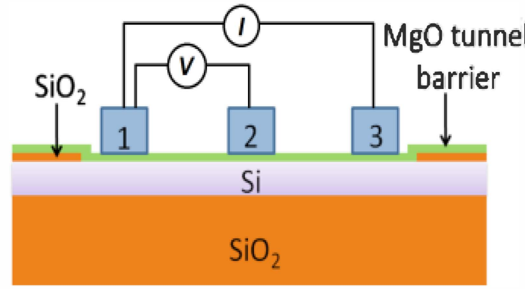

Fig. 1. 3-T setup for injecting spin polarized carriers in Silicon.

Because of the 3-terminal measurement geometry, the measured voltage (V) is the sum of: (i) the voltage drop across the part of the channel between 1 and 2 (V_C), (ii) voltage drop across the tunnel junction (V_J), and (iii) voltage drop due to the spin accumulation beneath the spin injection contact (V_S). Though the contributions coming from the first two terms are straight forward, origin of the third term lies on the spin-dependent tunneling of carriers from the ferromagnetic contact.The injection of a spin-polarized tunnel current from the ferromagnetic contact into the Si (which was p-type in our case) produces a spin-dependent imbalance in the hole population in the valence band of Si. The above imbalance results in different electrochemical potentials, μ↑ and μ↓, for the up and down spin directions, respectively, and a net spin accumulation, $\Delta\mu = \mu\uparrow - \mu\downarrow$. The spin accumulation of carriers underneath the contact results in the additional voltage 'V_S' which is related to the spin accumulation, Δμ, by the relation [37]:

$$V_S = TSP \times \Delta\mu / 2 \qquad (1)$$

where TSP is the tunnel spin polarization, a characteristic of the interface. When a magnetic field is applied perpendicular to the carrier spins in the semiconductor channel, spinaccumulation and hence the voltage decreases by means of the electrical Hanle effect [38]. Specifically on the application of transverse magnetic field, spins begin precession about this field and the spin accumulation decays following the relation[38]:

$$\Delta\mu(B) = \frac{\Delta\mu(0)}{(1+(\omega_L\tau)^2)} \qquad (2)$$

where τ is the spin lifetime and ω_L is the Larmor frequency given by $\omega_L = 2\pi g\mu_B B/h$, μ_B is the Bohr magnetron and g is the Lande´ g-factor, h is planck's constant. The decay in the value of Δμ with transverse magnetic field results in a similar decrease in value of V_S (and hence on the net voltage V):

$$V_S = TSP \times \frac{\Delta\mu(0)}{2(1+(\omega_L\tau)^2)} \qquad (3)$$

The contributions coming from the V_C and V_J show negligible changes with the applied magnetic field, so the variation in V with B is expected to occur only due to V_S [38] Fig. 4 shows the value of V_S determined from the change in V with B. By fitting V_S to above equations, the value of the spin coherence lifetime at room temperature was determined to be 276 picoseconds for NiFe/MgO tunnel contact. Using the experimentally determined electrical resistivity and the Hall effect data, the mobility (μ) of holes was found to be 151 $cm^2V^{-1}s^{-1}$. Using the Einstein relation, $D = \mu k_B T/e$, the diffusion constant (D) was estimated to be 3.9 cm^2s^{-1}. From this the spin diffusion lengths $L_{SD} = \sqrt{D\tau}$ were determined to be 328 nm.

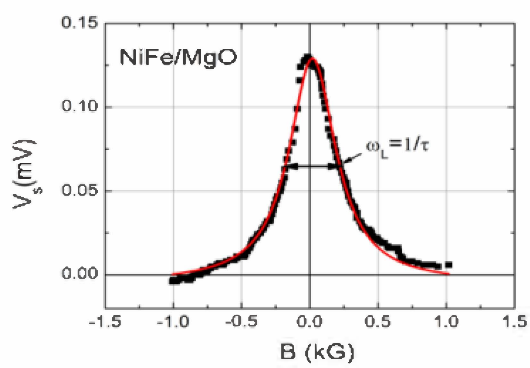

Fig. 2. Variation of spin accumulation voltage with transverse magnetic field.

III. Results on Radiation Detection:

Using our silicon-based 3-terminal spintronic devices, we performed tests to investigate the feasibility of using spintronic devices for radiation sensing (fig.3). All the tests were performed at room temperature. During the tests, a constant current of 100 μA was kept passing across the outer two contacts (terminal 1 and 3), injecting spin-polarized electrons from the ferromagnetic contact into the Si substrate. The voltage drop was measured across one outer and one inner contact (terminal 1 and 2).

The first test on our device was performed with a ^{137}Cs source. A baseline measurement was performed before exposing to gamma radiation. The voltage drop was measured to be 120 μV. This value decreased to 40 μV when the ^{137}Cs source was introduced. The 662 keV gamma flux at the detector was estimated to be 3.6E5 photons/s-cm^{2}during the test. The measurement results are shown below in fig. 6(a).The second set of experiments wasperformed using a ^{36}Cl source. ^{36}Cl undergoes β^- decay, emitting beta particles with endpoint energy of 709 keV. A baseline count was first taken without any presence of radiation. Immediately afterwards, two measurementswere performed with differentelectron flux. Different flux was achieved by offsetting the beta source. The measurement results are shown below in fig. 6(b).

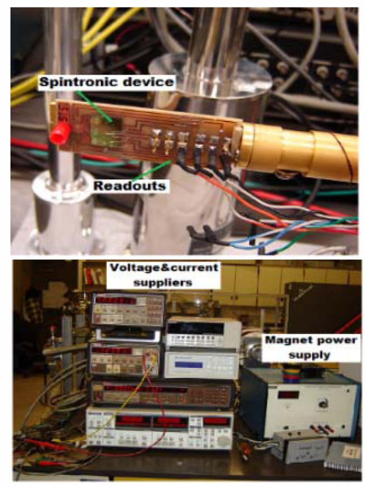

Fig. 3: Experimental set-up used in our preliminary study.

(a)
(b)

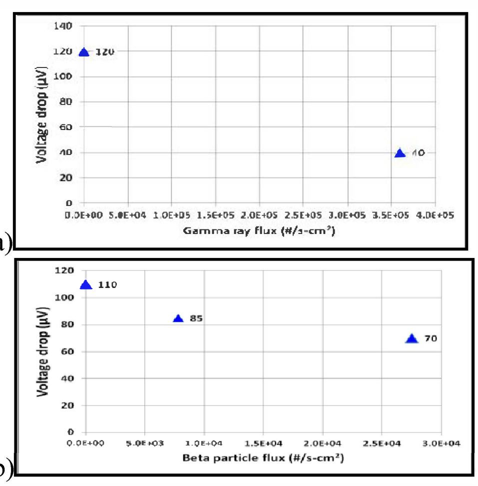

Fig. 4: Measured voltage drop as a function of gamma and beta particle flux.

As can be seen in above figures, for gamma as well as beta radiation, our test device showed very good sensitivity. Spin accumulation voltage beneath the spin-injector contact changed significantly upon exposure to radiation. The experimentally observed decrease in the spin accumulation voltage is understood to arise because of the change in the strength of Rashbha spin-orbit interaction (SOI) in the semiconductor channel caused by the radiation.

IV. FUTURE STUDIES

In this study, we used 3-terminal spintronic devices to investigate the feasibility of utilizing those for nuclear radiation detection. Though the 3-terminal devices are easy to fabricate and provide ample information about the spin coherence time, four-probe devices in non-local spin valve geometry are capable of providing much more precise and reliable information. So in the next step of our research, we are preparing 4-terminal spintronic devices.

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